Upper limits on O VI Emission From *Voyager* Observations

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ABSTRACT

We have examined 426 *Voyager* fields distributed across the sky for O VI ($\lambda\lambda$ 1032/1038 Å) emission from the Galactic diffuse interstellar medium. No such emission was detected in any of our observed fields. Our most constraining limit was a 90% confidence upper limit of 2600 photons cm^{-2} sr^{-1} s^{-1} on the doublet emission in the direction (l, b) = (117.3, 50.6). Combining this with an absorption line measurement in nearly the same direction allows us to place an upper limit of 0.01 cm^{-3} on the electron density of the hot gas in this direction. We have placed 90% confidence upper limits of less than or equal to 10,000 photons cm^{-2} sr^{-1} s^{-1} on the O VI emission in 16 of our 426 observations.

Subject headings: Galaxy: halo ISM: general

1. Introduction

There have been many detections of ultraviolet resonance line absorption by highly ionized, presumably hot, gas in the Galactic halo (e.g., Sembach & Savage 1992, Hurwitz & Bowyer 1996), but only three claimed detections of ultraviolet resonance line emission from this gas. First, Martin & Bowyer (1990) reported detections of the (unresolved) C IV ($\lambda\lambda$ 1548/1550 Å) emission in 4 out of their 8 lines of sight with a maximum strength of $(7.3 \pm 0.9) \times 10^{-8}$ ergs cm^{-2} sr^{-1} s^{-1}. They also detectected O III] (λ 1663 Å) emission at about half the intensity and much lower significance. Second, out of the ten Hopkins Ultraviolet Telescope (HUT) targets which could be profitably used for studies of the Galactic halo, Dixon et al. (1996) detected O VI emission in four directions at

levels on the order of 4×10^{-7} ergs cm^{-2} sr^{-1} s^{-1} (2.1×10^{4} photons cm^{-2} sr^{-1} s^{-1}), with 2 σ upper limits of roughly the same level on the other six targets. Finally, there have been three recent observations of O VI emission using the *FUSE* satellite all at a level of about only 5000 photons cm^{-2} sr^{-1} s^{-1}: Shelton et al. (2000, 2001) at (l, b) = (315.00, -41.33); and Dixon et al. (2001) at (l, b) = (284.2, 74.5) and (l, b) = (57.6, 88.0).

The most constraining upper limit is the *MINISAT-01* 90% confidence upper limit of 2.5×10^{-8} ergs cm^{-2} sr^{-1} s^{-1} (1200 photons cm^{-2} sr^{-1} s^{-1}) from Edelstein et al. (1999) with earlier limits of about 1.6×10^{-7} ergs cm^{-2} sr^{-1} s^{-1} (7600 photons cm^{-2} sr^{-1} s^{-1}) from Korpela et al. (1998) and Holberg (1986). Note that all values cited for the O VI emission are for the integrated emission over both lines of the doublet.

Murthy et al. (1999) have reprocessed 17 years (1977 – 1994) of data from the *Voyager* 1 and 2 archives with a focus on the continuum emission due to dust scattering. In the present paper, we will discuss limits, from the same data set, on O VI (1032/1038 Å) line emission from the ISM. Although new instruments are now providing important results, the *Voyager* data are still the only source of information on the O VI emission over many different lines of sight.

2. Observations and Data Analysis

The two *Voyager* spacecraft were launched in 1977 and have taken FUV (500 - 1700 Å) spectra of astronomical objects ever since. Each spacecraft includes a Wadsworth-mounted objective grating spectrometer (UVS) with a field of view of $0\overset{\circ}{.}1$ x $0\overset{\circ}{.}87$ and a spectral resolution of 38 Å for aperture filling diffuse sources. A full description of the UVS instruments and the *Voyager* mission is given by Holberg & Watkins (1992).

The data processing is described in Murthy et al. (1999). Because we were only interested in the diffuse background, all other observations (planets, stars and nebulae) were discarded. The remaining data consist of 426 observations of diffuse background. The O VI doublet ($\lambda\lambda$ 1032/1038 Å) is clearly visible in the *Voyager* spectra of bright sources such as supernovae remnants (Blair et al. 1995) and the Eridanus superbubble (Murthy et al. 1993), where the doublet is much brighter than the heliospheric hydrogen Ly β (λ 1026 Å) emission. However, the O VI emission from the diffuse halo gas is much less than the Ly β emission on whose wings it lies. Fortunately, because the Lyman lines are optically thick, the Ly β/Ly α ratio is constant throughout the heliosphere and we can use the Ly α line to scale the Ly β line. We determined the ratio between the two lines using UVS observations in which only the heliospheric lines were present and then used this empirical ratio to scale the Ly β line in each observation (see Murthy et al. (1999) for a full description of this procedure). We subtracted this scaled Ly β intensity from the observed spectrum and determined the O VI upper limit from the remainder.

Because the Ly β line is at almost the same position as the O VI line, there is a tradeoff between their respective derived intensities. Note, however, that the difference in the central wavelengths

of the Ly β and O VI emission is large enough (1 resolution element) that O VI cannot fully, or even largely, replace the Ly β contribution. In our procedure, we have restricted the heliospheric Ly β/Ly α ratio to fall between empirically determined limits; if, on the other hand, we allow the Ly β/Ly α ratio to vary freely, our limits on the O VI emission will be correspondingly poorer. We have carried out this exercise for each of our targets but, because of the varying amount of heliospheric emission, cannot compare points on an individual basis. In general, our limits go up (become less constraining) by a factor of 2 – 3. Thus our best upper limit rises from 2600 photons cm^{-2} sr^{-1} s^{-1} to 8500 photons cm^{-2} sr^{-1} s^{-1} and the number of pointings with O VI limits under 50,000 photons cm^{-2} sr^{-1} s^{-1} drops to 127 from 244. (Details of the individual targets are available from the authors on request.)

Edelstein et al. (2000) have claimed that Holberg (1986) and Murthy et al. (1999), have significantly underestimated the errors in the *Voyager* data. As the data analysis in this work rests heavily on the earlier papers, particularly that of Murthy et al. (1999), we are compelled to address these criticisms. A careful reading of the Edelstein et al. paper shows that there are virtually no differences between their results and ours, despite their claims. From their Table 2 Edelstein et al. obtain a 1 σ uncertainty of 125 photons cm^{-2} sr^{-1} s^{-1} Å^{-1}, identical to the limit claimed by Holberg (1986). However, they also obtain a residual of 320 photons cm^{-2} sr^{-1} s^{-1} Å^{-1} whereas Holberg (1986) found a null signal. This difference can be traced to Edelstein et al. estimating two large numbers from a figure in Holberg (1986), subtracting the two and claiming that as the residual. If they had actually used the original data in digital format, the correct procedure, their results would have agreed exactly with Holberg (1986). Importantly for this work, and contrary to their claims, Edelstein et al. (2000) have shown that the counting errors in our analysis procedure are reasonable.

Because the signal in the *Voyager* spectra is dominated by the RTG particle background (due to radioactivity in the radioisotope thermoelectric generator) and the scattered Ly α, we have explored the possibility that systematic errors in the subtraction of the two components are affecting our O VI limits. Should there be a feature in either of these components coincidentally at the position of O VI, we would expect the O VI limits to be correlated with that component, because the strength of that feature would be necessarily correlated with the level of the continuum (the sum of the RTG and Ly α contributions). Over the 17 years of *Voyager* observations, both the RTG level and the Ly α emission declined: the former because of the decline in the radioactivity of the plutonium power source and the latter because of the increasing distance of the spacecraft from the Sun. Thus, if there were any significant systematic errors associated with the background subtraction, our O VI limits would be strongly correlated with the year of observation. No such effect is detectable in our data (shown in the case of the Ly α emission in Figure 1), implying that systematic effects due to the subtraction of the RTG and Ly α backgrounds are unimportant.

We can demonstrate empirically that our quoted error bars are reasonable through a listing of each of the errors in one of our targets (Table 1). Note that we have arbitrarily chosen the location with our most constraining O VI limit. We have listed in Table 1 the integrated counts under the

O VI line in the total spectrum and in each of the modeled components of the raw *Voyager* data: the RTG spectrum; the Ly α template; Ly β emission; and the diffuse continuum (due to dust-scattered starlight). The poisson errors are also listed, with the RTG and total errors reflecting the fact that each RTG event generates 3 counts (Holberg 1986). From these errors we then calculate a total uncertainty, assuming uncorrelated errors. For this target we obtain a 1 σ uncertainty of 308 counts corresponding to a signal of 1400 photons cm^{-2} sr^{-1} s^{-1}. This is entirely consistent with the 90% confidence level of 2600 photons cm^{-2} sr^{-1} s^{-1} that we derived using our modeling procedure (the modeling is described in detail in Murthy et al. (1999)). Our quoted uncertainties have taken into account all the statistical errors and come from a χ^2 minimization according to the procedure described by Lampton et al. (1976). Essentially, we changed the value of the O VI emission, while allowing the other parameters to vary freely through the allowed parameter space, until the χ^2 emission rose to unacceptable levels.

3. Results and Discussion

We detect no O VI emission in any of 426 UVS observations of the diffuse radiation field but do set upper limits on such emission in each direction. The best of these limits is 2600 photons cm^{-2} sr^{-1} s^{-1} (5.0×10^{-8} ergs cm^{-2} sr^{-1} s^{-1}) in the O VI resonance line doublet in the direction (l, b) = (117.3, 50.6). This direction is quite close to HD 121800 (l, b = 113.0, 49.8 , spectral type B1.5 V, distance = 2.2 kpc) towards which Hurwitz & Bowyer (1996) obtained a O VI column density of 1.1×10^{14} cm^{-2} using ORFEUS. Using these values and Equation 5 of Shull & Slavin (1994), and confining the temperature range to that for which the fraction of oxygen atoms in the O VI state is within 10% of its maximum value in collisional ionization equilibrium plasma (T = $2.2 - 6.4 \times 10^5$ K — Shapiro & Moore (1977)), we find an upper limit on the electron density of less than 0.010 cm^{-3}. Assuming that the emitting gas has a solar abundance of helium atoms and that the hydrogen and helium are fully ionized, there will be 1.9 particles per electron and thus the thermal pressure will be less than 12,000 K cm^{-3}, close to the thermal pressure of 15,000 K cm^{-3} in the Local Bubble derived by Snowden et al. (1998) from observations of the 1/4 keV soft X-ray flux seen by ROSAT.

The 94 locations in which we set 90% confidence upper limits of better than 5×10^{-7} ergs cm^{-2} sr^{-1} s^{-1} (25,000 photons cm^{-2} sr^{-1} s^{-1}) are plotted in Figure 2 and those in which we set limits of better than 2×10^{-7} ergs cm^{-2} sr^{-1} s^{-1} ($\approx$ 10,000 photons cm^{-2} sr^{-1} s^{-1}) are listed in Table 2. Several of our observations are near the locations observed by Dixon et al. (1996) using HUT and we both set similar upper limits in those (with our *Voyager* limits in general being more constraining). Only in their Target 3 (UGC 5675; l = 218.2, b = 56.4) do we obtain inconsistent results, with Dixon et al. (1996) quoting a flux of 23,000 $\pm$ 6000 photons cm^{-2} sr^{-1} s^{-1} while we place a 90% upper limit of 10^4 photons cm^{-2} sr^{-1} s^{-1}at (l, b) = (216.8, 55.3) — about 1° away. Of course, it is entirely possible that there are truly spatial variations of this scale in the ISM.

We also have several observations near the four high latitude locations where Martin & Bowyer

(1990) detected C IV emission but in none can we do more than say that the O VI/C IV ratio is not inconsistent with the theoretical ratios reported from a variety of physical conditions (e.g. cooling flows: Edgar & Chevalier (1986); shock heated gas: Hartigan et al. (1987); fountains: Benjamin & Shapiro (1993); halo supernova remnants: Shelton (1998)).

4. Conclusion

Very recent results concerning galactic diffuse O VI emission include the *FUSE* detections by Shelton et al. (2000, 2001) and Dixon et al. (2001) at a level of 5000 photons cm^{-2} sr^{-1} s^{-1} and the *MINISAT-01* all-sky upper limit of 1200 photons cm^{-2} sr^{-1} s^{-1} by Edelstein et al. (1999). Combined with the present *Voyager* upper limits, it appears that much of the sky has an O VI emission of significantly less than 10,000 photons cm^{-2} sr^{-1} s^{-1}. Only the 4 HUT detections of Dixon et al. (1996) show higher fluxes. A mission dedicated to the observation and mapping of faint line emission from the Galactic halo would surely yield bountiful results.

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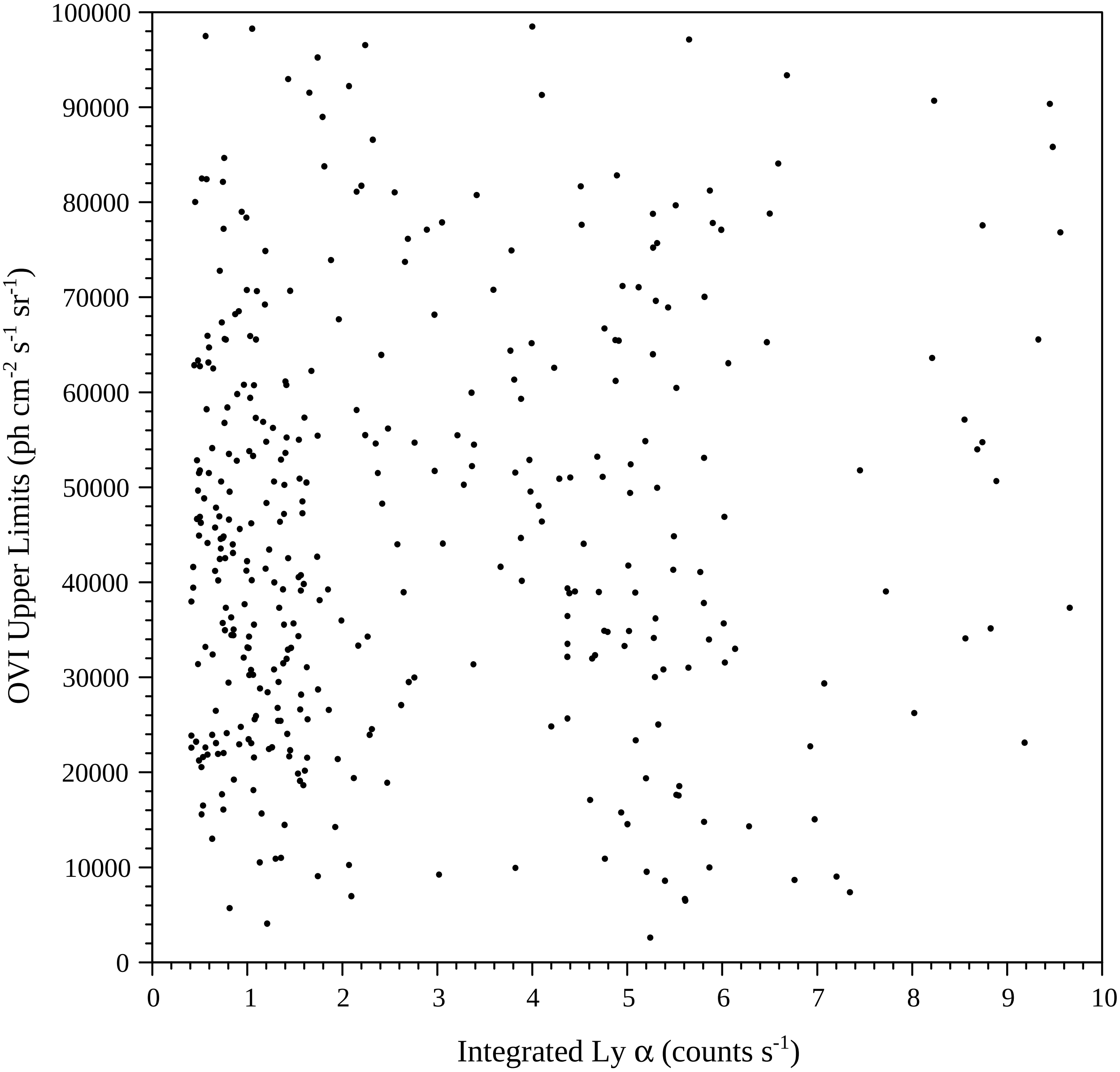

Fig. 1.— We have plotted the derived O VI upper limits against the integrated counts in the Ly α line. There is no correlation between the two. Such a correlation might be expected if systematic errors were an important contributor to the O VI limits. Similar plots are obtained when the O VI limits are plotted against the relative RTG strength or the diffuse continuum - none of the different components are correlated, indicating that systematic errors are unimportant in our analysis.

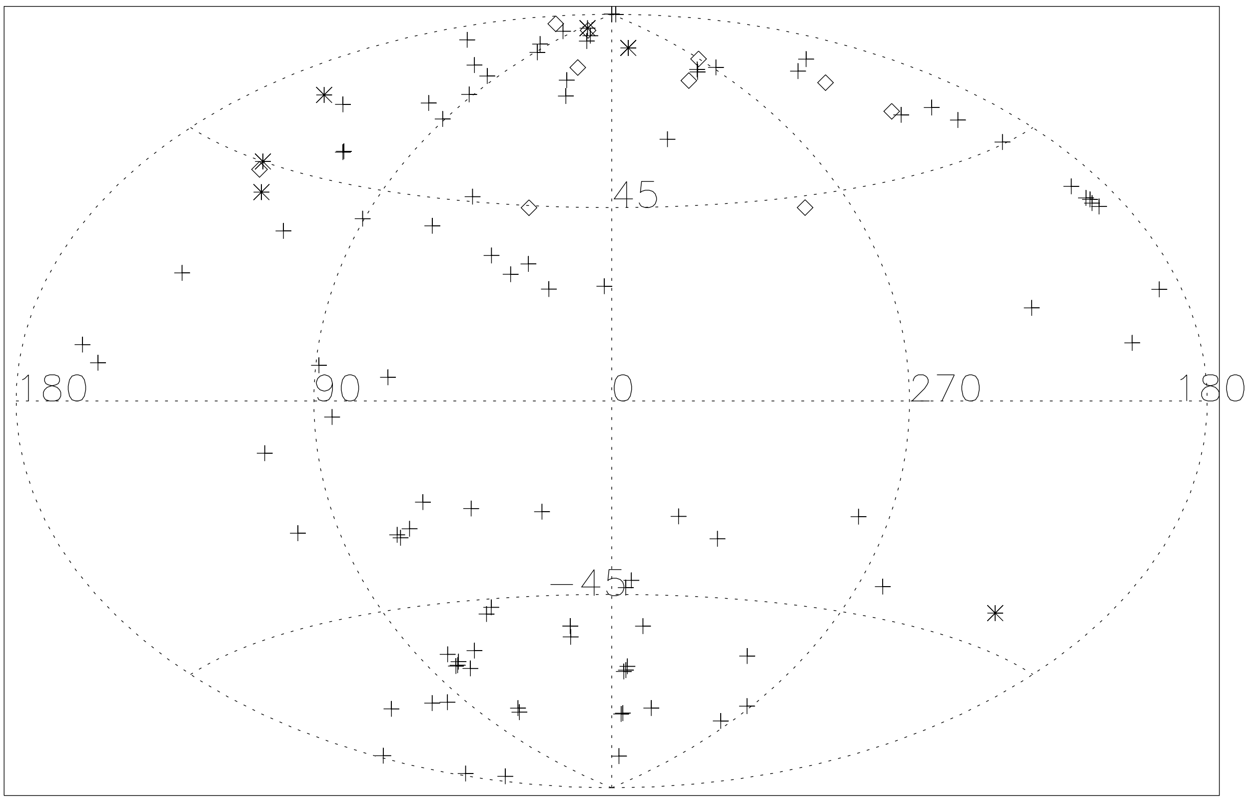

Fig. 2.— All of the *Voyager* observations in which we were able to set upper limits of less than 5×10^{-7} ergs cm^{-2} sr^{-1} s^{-1} (25,000 photons cm^{-2} sr^{-1} s^{-1}) are plotted as plus signs on an Aitoff map of the sky with the origin at the center and 180° at the left. The Dixon et al. (1996) targets are plotted as diamonds and the C IV detections of Martin & Bowyer (1990) are plotted as asterisks. In one direction in common (see text), we place a 90% confidence limit that is about half the claimed detection by Dixon et al.; however, given both sets of uncertainties and the different locations, we cannot rule out their claimed value.

Table 1. Statistical Limits on the Modeled Components

	Total Counts	Poisson Error
Total	113000	194
RTG	91200	174
Ly α	2300	48
Ly β	11700	108
Diffuse Continuum	11800	109
Total Error		308

Table 2. Best *Voyager* O VI Upper Limits

l degrees	b degrees	90% Confidence Upper Limit on O VI Emission photons cm^{-2} sr^{-1} s^{-1}
117.3	50.6	2,600
272.5	-67.4	4,100
67.8	5.2	5,700
60.3	-22.5	6,500
117.3	50.8	6,700
200.7	9.6	7,000
71.6	-59.6	7,400
189.6	32.3	8,600
91.1	61.4	8,700
115.7	72.6	9,000
32	70.5	9,100
331.7	60.5	9,200
99.3	80.3	9,500
225.7	68.3	9,900
190	33.3	10,000
216.8	55.3	10,000
346.6	-52.3	11,000